TECHNICAL ANNEX

Alternatives to HCFCs/HFCs in unitary air conditioning equipment at high ambient temperatures

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Avoiding replacement of R22 by high GWP HFCs

Owing to the accelerated phase-out schedule for developing countries which are Parties to the Montreal Protocol (Article 5), the replacement of the ozone-depleting and climate damaging HCFCs (primarily R22) has become an important political issue. R22 is an efficient "all-around" refrigerant for a wide range of evaporation temperatures, from -40°C to +10°C. It is mainly used for air conditioning (air-to-air systems) followed at some distance by commercial refrigeration. The thermodynamic properties provide high performance also at high ambient temperatures (> +40°C) which occur in summer days in many developing countries. R22 has become and still is the most widespread refrigerant in these regions. The question arises whether the replacement of R22 by refrigerants with lower GWP could provide the same energy efficiency, at both moderate and high ambient temperatures.

This technical annex focuses on stationary air conditioning (air-to-air; also called unitary systems) because of the outstanding importance of this sector for the refrigerant demand. The sector currently accounts for almost half of the total refrigerant consumption (~ 400 kt/y) of developing countries. The demand in sales number of air conditioning units is projected to increase four-fold until 2030. This steep rise is partly caused by ODS substitution during the same time-period but to a much larger extent by economic growth. India e.g. shows particularly large growth potential for unitary air conditioning equipment. Sales of units are projected to increase by the eight-fold by 2030 compared to 2015[1]. More than one third of India's population lives in regions with monthly mean maximum daily temperature > 40°C in May and often also June. The temperatures are higher than in Middle East states like Bahrein or Qatar and almost as high as in Kuwait or Saudi Arabia (Riyadh).

In industrialized countries, R22 has mostly been replaced by HFC blends with high GWP such as R410A. If developing countries would go the same way, the global warming impact of the air conditioning sector could jeopardize the worldwide efforts to stop or even reduce emissions of fluorinated greenhouse gases. Needless to say that industrialized countries themselves bear the responsibility to replace high GWP HFCs by low GWP alternatives.

[1] http://www.green-cooling-initiative.org/country-data/#!unit-sales/unitary-air-conditioning/absolute

Thermodynamic suitability of R22 alternatives for high ambient temperatures

Since pure HFCs did not match the properties of R22, the Chemical industry developed blends of HFCs for air conditioning: R410A which substituted the first replacement blend R407C due to better performance under normal temperature as it is typical of industrialized countries. For operation at high ambient temperature, however, the blend R410A (like R404A in commercial refrigeration) is no good choice because their efficiency (and refrigeration capacity) decreases at a notably higher rate than R22, beyond ambient temperatures of 40°C.

In order that the efficiency and cooling capacity of a system does not degrade rapidly at higher ambient temperatures, an important characteristic is that it should have a critical temperature substantially higher than the ambient temperature at which it is expected to operate. For example, with an ambient temperature of 40°C, the critical temperature would be higher than about 80°C in order that a substantially larger (and thus more costly) condenser is not needed to compensate.

The critical temperature is the temperature above which there is no distinct difference in density between the liquid and the gas phase and hence phase-change from a gaseous to a liquid state is no longer possible. Consequently, this prevents condensation at constant temperature. Roughly, the higher the critical temperature the better the refrigerant will perform under high ambient temperature conditions. Table 1 provides the critical temperatures for a number of HCFC and HFC refrigerants and of HC-290 (propane).

Table 1: Critical temperatures of refrigerants and refrigerant blends

	Critical Temperature Tc
Refrigerant	°C
HCFC-22	96.1
R410A	71.4
HFC-125	66.3
HFC-32	78.1
R404A	72.0
HFC-143a	73.1
HC-290	96.7

Table 1 shows that at high ambient temperature R410A (and R404A) are not the best options to replace R22 (comparing their critical temperatures of 71.4 °C and 72°C, respectively, with 96.1 °C). In the case of R410A this mainly results from the 50% share of HFC-125 (other 50%: HFC-32) with a critical temperature of only 66.3°C. The natural refrigerant HC-290 shows a critical temperature like R22. It should therefore perform well under HAT.

Performance loss of HFCs compared to R22

Given the differences in critical temperature, the question arises to which extent the energy efficiency drops compared to R22 at high ambient temperature. In general, capacity and efficiency decline for all refrigerants as the heat-rejection (condensing) temperature increases. However, some refrigerants show significantly higher efficiency decrease compared to the efficiency decrease of R22.

Table 2 presents calculated efficiencies (COP) for a number of refrigerants used in air conditioning at three condensing temperatures: The table includes efficiencies at condensation temperatures of 35°C (moderate condensing temperature), 60°C and 65°C, the latter representing high condensing temperatures. 60°C and 65°C condensation may occur at ambient temperatures in the range of 40-45°C. It should be noted that daytime peak temperatures may significantly exceed the monthly mean maximum temperature. The ambient temperature will increase even higher when the condenser, which is often located on flat roofs without adequate ventilation, is exposed to direct solar radiation.

Table 2: Refrigerant efficiencies at various condensing temperatures (COP)

Refrigerant	Condensing temperature °C		
	35°C	**60°C**	**65°C**
HCFC-22	5.08	**2.64**	2.29
HC-290	5.09	**2.58**	2.23
HFC-32	4.85	**2.43**	2.09
R410A	4.80	**2.32**	1.95

Source: Lambert Kuijpers, Roberto Peixeto: XIX/8 Report on HCFC Alternatives for High Ambient Temperature Regions, Presentation at OEWG-30, Geneva, 15-18 June 2010.

When comparing the COPs at 65°C, Table 2 shows that R410A (COP 1.95) is not an energy efficient option to replace R22 (COP 2.29). Given an equivalent equipment design, the energy performance is 15% lower at 65°C condensing temperature. At 65°C, pure HFC-32 (COP 2.09) is closer to R22 but still shows a difference of almost 9%. These drawbacks in efficiency imply that extra design efforts have to be made by equipment manufacturers, e.g. increasing the heat exchanger area, in order to achieve comparable efficiency. Such measures cause extra manufacturing costs for the systems.

Regarding R32 a specific disadvantageous characteristic may be mentioned, arising from its low specific heat. The temperature of the refrigerant gas after the compressor (discharge temperature) is notably higher than that for R22 (for the same operating conditions). Therefore, at high ambient temperatures the discharge temperature is relatively high. This – especially in combination with the higher reactivity of R32 - infers reliability issues with the compressor (and other parts of the system). There are several options to help minimise this high discharge temperature, such as wet suction and superheat control, with the most preferred approaches being liquid or vapour injection. Depending upon which option is chosen and how it is implemented, there can be a loss of capacity or efficiency or increase in cost for additional components or complexity and similarly a compromise on reliability.

In contrast, R290 has performance characteristics similar to HCFC-22. According to table 2, the COP of R290 (2.23 at 65°C) is ~2.5% lower in relation to R22. This drawback at 65°C is however not essential. At high ambient temperatures the thermodynamic characteristics of R290 are close enough to R22 so that the current products that employ R22 could be re-engineered to employ HC-290 instead; the compressor can be the same. The discharge temperature is substantially lower than R22 and does not cause specific efforts or costs. The main use limitation related to R290 is its high flammability (class A3), which restricts the indoor use to charges < 1.5 kg. In addition, the production lines of the manufacturers must be adapted.

Extra efforts and cost for maintaining required efficiency with HFCs

Nevertheless, even under high ambient temperature R22 could be replaced by high GWP HFC blends (R410A) or pure HFCs (R32) at equal efficiency if the application engineers adapt the equipment's capacity accordingly. Upsizing of system components, notably of the area of heat exchangers (condenser, evaporator), is a viable and realistic option to compensate for loss in efficiency of any refrigerant. In most cases, equipment will need to be sized 5-15% to compensate for the lower capacity at high ambient temperature, implying higher product cost. The associated costs can be approximated as proportional to the respective capacity degradation.

In this regard it should be pointed out that such technical measures will not reduce the potential damage to climate. The GWP of HFC-32 is 675, which is significantly lower than 1,810 of R22. If, however, R32 would be the only R22 replacement option and if at the same time the refrigerant demand triples until 2030[2], the potential global warming impact of R32 would not be lower but the same as the current impact of R22. In India e.g., the climate damaging effect would even double.

Lower replacement cost with hydrocarbon refrigerants

An alternative approach is to spend additional money not for adaptation of HFC equipment to the efficiency level of R22 but for safe operation of high efficient flammable hydrocarbon refrigerants wherever their use is possible. The environmental benefit is that the substitutes have a very low GWP; a technical advantage is the use of common R22 compressor technology. The expenditure to compensate for efficiency loss of HFCs is considered substantially higher than the additional cost for safe manufacture and safe and efficient operation of flammable low-GWP hydrocarbon refrigerants[3].

Stationary air conditioning with air-to-air systems (in contrast to chillers which are air-to-liquid systems) include hermetically sealed (leak-tight) portable and window-mounted systems (capacity < 5 kW), single-split systems for room air conditioning (up to 15 kW), as well as comparably big multisplit and rooftop systems for more than one room in a building (capacities > 15 kW). The R22-charges of portable devices are small (max. 0.75 kg), whereas the charges of single split systems range from 0.7 to 3 kg. Multisplit equipment is charged with up to more than 10 kg per unit.

At high ambient temperature, R290 is the most efficient alternative to R22. According to the current safety standards, its high flammability limits the use to 1 kg indoor charge. This requirement can easily be met by the portable units. Regarding split-type systems including multisplit, R290 is not suitable to cover the full range of capacities. Even considering that the thermodynamic properties of R290 allow one-third to half of the charge compared to R22 for the same capacity, its application at normal ambient temperature is limited by current safety standards to capacities < 9 kW[4].

At high ambient temperature, 1 kg of R290 cannot achieve the same capacity as under moderate temperature. The maximum capacity per unit with charge < 1 kg can be estimated at 7 kW. Systems < 7 kW represent ca. 80% of the market by number of units, and systems > 7 kW only 20%. However, considering the lower R290 charges per unit, the share of R290 in the total refrigerant mass of the sector is not proportional to the number of units but smaller. It is assumed here that at high ambient temperature R290 can replace > 50% of the R22 quantity. Its charge limits in the current standards do not allow operation of single split units > 7 kW and of multisplit systems[5]. Therefore, in order to

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[2] In the case of R22 replacement by R32, a four-fold growth in capacity could be achieved by the three-fold refrigerant mass only because charges of R32 need to be by 20% lower for the same refrigerating capacity.

[3] This position is based on cost data of replacement technologies which underlie the sector-specific calculations of abatement cost of high GWP HFCs by low-GWP alternatives and have been carried out in the preparatory study Schwarz et al 2011 for the European Commission.

[4] In the recent TEAP report (pre-draft) is said that the "refrigerant charge can be reduced as low as 0.11 kg/kW or even less". With a charge limit of 1 kg, this relates to 9 kW.

[5] The use of R290 in split/multisplit applications > 7 kW is not principally excluded by the standards since the safety restriction refers to the direct mode only. Indirect operation with heat transfer fluid (HTF) for indoor evaporation can well cover the high-capacity sector. However, product costs are notably higher in relation to direct systems. This is first of all a result of the need to improve the efficiency relative to direct operation,

quantify the appropriate R22 replacement options, we divide the split/multisplit sector in two sub sectors, one below 7 kW and another above 7 kW. In the latter, R290 is not a realistic option.

It should be emphasized that all other alternatives to R22 or R410A with a low or medium GWP, that are currently under discussion or already in use, are likewise classified as flammable. This refers to HFC-32, unsaturated HFCs (HFO) and blends of R32 with HFOs which are included in the ASHRAE safety class A2L (lower flammability). However, compared to the "highly" flammable hydrocarbon refrigerants (safety class A3), the recently revised ISO 5149 allows maximum charges of A2L refrigerants that are 10-12 times higher than the charge limit of R290. In reality, 10-12 kg charges are possible. In terms of the safety, A2L refrigerants are suited to completely cover the single-split subsector > 5 kW and also the multisplit subsector, in direct (DX) mode.

Table 2 shows that, apart from its comparably high GWP_{100y} of 675 (4^{th} AR), pure R32 (A2L) is the second most efficient refrigerant option amongst the commercially available alternatives to R22 for unitary air conditioning equipment at high ambient temperatures. There are a considerable number of R32/HFO blends under development. Some of them are promising R22 replacement candidates with efficiencies similar to R32 and with GWP of only one third of the R32 value[6]. However, it must be pointed out that the first R32/HFO blends will be commercially available not before 2017. In the meantime, R32 is considered an R22 replacement option for unitary air conditioning equipment with capacities > 7 kW at high ambient temperatures. Many of the proposed HFC/HFO blends exhibit much lower discharge temperatures than R32.

In order to visualize the suitability of low GWP alternatives we use "traffic lights". The colour of the dots indicates the degree of suitability as replacement for ODS or high-GWP HFCs.

	Common refrig.	Cons. A5 2015	HC direct	HC in direct	HFO	R32	*R32-HFO blends*
GWP			3	3	< 10	675	*200-400*
Portable/Windows	R22	30 kt/y	🟢	🔴	🔴	🔴	🟡
Single Split < 7kW	R22	90 kt/y	🟢	🔴	🔴	🔴	🟡
Split/Multi. >5kW	R22	80 kt/y	🔴	🔴	🔴	🟢	🟡

🔴	Efficiency too low or cost too high compared to other alternatives
🟡	Efficient. Safe. But costly and no short term availability
🟢	Efficiency high. No or acceptable additional cost. Short term availability

Immediate and safe application of R290 wherever possible

R22 replacement with natural refrigerants is immediately possible and can cover almost two thirds of the current and future refrigerant demand for unitary air conditioning equipment. If by 2030 in developing countries the refrigerant mass in the sector would consist of R290 by 60% and of R32 by

which requires more material (extra heat exchangers, pump, piping). These extra efforts result in increased costs by 10% to 30%. In this paper, indirect operation with R290 is not considered a realistic replacement option for developing countries.

6 According to the 2013 AREP performance tests, there are at least two A2L blends that come into question as R22 alternatives owing to their high efficiency and comparably low GWP: L20 and LTR6A. The former has a GWP of 331 (4^{th} AR), the latter of 207 (4^{th} AR). In both cases the energy efficiency was measured approx. 98% in relation to R22, a loss that can be compensated by system design. The manufacturer of L20 states: "At high ambient temperature (46°C) Solstice L20 shows performance similar to R22 and better than R410A and R32".

40%, the global warming impact from the projected triple refrigerant demand could be reduced to 40% of the current level caused by R22. Through successful introduction of R32/HFO blends instead of pure R32, a further reduction to 20% appears to be achievable. It must be pointed out that such a successful reduction in global warming impact first of all relies on a broad application of hydrocarbon refrigerants like R290, wherever it is feasible under the given safety standards.

Clearly, large scale application of hydrocarbons in stationary air conditioning systems poses a major challenge to manufacturers of components and equipment units to provide the sufficiently high number of units. The expansion takes considerable amounts of time. However, there is no lack of refrigerants at all, and the technologies are available. Natural refrigerants like R290 exhibit performance like R22 at high ambient temperature and have proven reliable and efficient for many years not only in industrialized countries but also in developing countries.